The New Tropospheric Product of the International GNSS Service

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BIOGRAPHY

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Gerd Gendt studied Mathematics at the University of Rostock, Germany. He obtained a doctorate in Mathematics in 1975 from the University of Rostock, and habilitated in Satellite Geodesy at the University of Postdam, Germany, in 1991. In 1974 he entered the Central Institute for Physics of the Earth in Potsdam. Since 1992 he is Senior Scientist at the GeoForschungsZentrum Potsdam (GFZ), where he is responsible for the IGS Analysis Center, and since 2003 he is the Analysis Coordinator of the IGS.

ABSTRACT

The International GNSS Service (IGS) has been producing tropospheric product that are based on combined contributions from several IGS Analysis Centers (AC). These products contain time series of total zenith delay from a large subset of the IGS network of ground-based GPS receivers. The IGS has recently adapted a new method for the derivation of the tropospheric products. Each new product consists of a time series of total zenith troposphere delay at 5 minute intervals from a set of IGS ground sites. Total zenith delay values are estimated with the precise point positioning (PPP) approach, using the IGS combined GPS orbit and clock solutions, and RINEX files generated by each site.

We compare this new approach for generating the IGS tropospheric products with the previous approach, which was based on explicit combination of total zenith delay contributions from the IGS ACs. The new approach enables the IGS to rapidly generate highly accurate and highly reliable total zenith delay time series for many hundreds of sites, thus increasing the utility of the products to weather modelers, climatologists, and GPS analysts. In this paper we describe this new method, and discuss issues of accuracy, quality control, utility of the new products and assess its benefits.

INTRODUCTION

Continuous and well distributed measurements of water vapor are of great interest for numerical weather forecast, climate research, and atmospheric studies. It has been shown that a ground based GPS receiver can provide continuous information on vertical integrated water vapor at a site (Alber et al. 1997; Rocken et al. 1997; Rocken et al. 1995; Rocken et al. 1993; Ware et al. 1997; Ware et al. 1993). The existing global and regional networks of permanent GPS receivers installed for geodetic and navigational applications can be used with marginal additional cost for determination of atmospheric water vapor with high temporal and spatial resolution. In fact, in regions where dense networks with permanent receivers are established, many projects had been under way in which the impact of GPS derived water vapor on the improvement of weather forecast are studied (Businger et al. 1996; Ware et al. 2000).

In the past some experiments had demonstrated the capability of IGS (Gendt 2004; Gendt 2002; Gendt 2000; Gendt 1998a; Gendt 1998b). In 1997 IGS has decided to use its global tracking network to contribute to atmospheric water vapor monitoring and to provide a global reference for studying global climate change. Within the IGS, a network of globally distributed sites are analyzed on a daily basis. The zenith path delay (ZPD) values obtained can be converted into precipitable water vapor (PWV) and made available to the international science community.

In order to serve the global science community better a new approach to the IGS tropospheric product has been suggested in early 2003. The new IGS Tropospheric Product and related services have now passed a long testing period, and are currently operational and ready to use. The background information about the rationale behind the new approach to the IGS Tropospheric Product, the nature and features of the new product and services, and the challenges of calibrating the many meteorological packages in the IGS network are described in the following sections.

LEGACY PRODUCTS

The legacy IGS tropospheric combination process is derived from individual contributions of ZPD estimates from each IGS ACs. The IGS Combined Tropospheric Product is an attempt to optimally combine these contributions for each site. There are two types of legacy IGS tropospheric products with difference latencies: "Final", and "Ultra-Rapid (UR)". The Final product is based on the IGS "Final", the most precise combined GPS orbit and clock products, and on daily RINEX files. The Final product is produced weekly with less than 4 weeks of latency. The UR product is based on the IGS ultra-rapid GPS orbit and clock products, and on hourly RINEX files. The latency is up to three hours after data has been collected.

Tropospheric parameters, in form of ZPD of the neutral atmosphere, are estimated by the IGS ACs in their operational daily work. In average six ACs regularly contribute their solutions using slightly different and evolving estimation strategies. The sampling rate applied for AC's analyses is typically 1-2 hours as of this writing. IGS legacy tropospheric product is based on the submitted individual AC's solution. The combination process starts with the derivations of 2 hours mean values of ZPD for each AC. The mean is formed epoch-wise taking into account AC dependent biases not to get jumps by missing data. Additionally, the mean daily station coordinates are computed. Here, a homogenization of all used antenna heights and types is performed, so that all coordinates refer to the same physical point. The Final legacy product is a weekly file for each site containing piece-wise continuous weighted mean of the ZPD values every two hours. This file also contains some statistics on the differences of each IGS AC with respect to the IGS Combined Product. Since January 1997 (GPS week 890) the IGS regularly generated a combined tropospheric product.

To facilitate the exchange of the individual submissions and the distribution of the combined products, special file formats were developed by following the philosophy developed for the SINEX format. The files for the submissions and for the results practically have the same structure. The main difference is that the submission file contains estimates of all sites for one day while the combined file contains the estimates for only one site for a whole GPS week allowing a simple compilation of longer time series.

The quality of the product (internal consistency between ACs) is at the level of 4-5 *mm* in the ZPD stddev, which corresponds to ≤ 1 *mm* in PWV. The largest stddevs can be found in the equatorial region. The magnitude of the stddev is of course highly correlated with the magnitude in the repeatability of the estimated station coordinates. The biases have no significant global bias and are even smaller scattering from site to site is about ± 3 *mm*. The bias is highly correlated with the station height. The biases are smaller for fiducial, fixed sites (ALGO, KOKB) and rather high for sites with a weak station coordinate solution. However, if an AC changes its estimation strategy, the change in the analysis parameters of the AC can be easily observed from the ZPD time series (ex. elevation cutoff angle change, mapping function change).

The GPS derived PWV estimates can be compared with Water Vapor Radiometer (WVR) measurements to get a measure for the absolute accuracy. Comparisons with collocated techniques were performed for Potsdam site where WVR measurement is available. The GPS derived ZPD was converted into PWV and compared to the WVR. AC's GPS solutions monitor the fluctuations in the water vapor with high accuracy. The agreement of the GPS results with the WVR is at the 1 *mm* level in bias with the best agreement is for the combined series. The bias may have various reasons, e.g. the WVR itself (calibration) or GPS modeling deficiencies (antenna phase center patterns, mapping functions, satellite antenna offsets). The stddev of the difference approaches ± 0.5 *mm*. The difference between the GPS solutions is smaller than their differences to the WVR measurements.

LIMITATION OF LEGACY PRODUCTS

The IGS produces two legacy tropospheric products: "Final" with latency of several weeks, and "Ultra-Rapid (UR)" with latency of 5-6 hours relative to the oldest data point. The quality of both products is good, quoted at 4 mm for the Final product, and 6 mm for the UR product based on inter-comparison among the contributing AC solutions. Both these products are derived through a complex procedure that combines individual solutions from several ACs. Both products have been available in their present form and quality for some time but, unfortunately, only a few users retrieve the IGS tropospheric products. So why are the products not used despite their fairly high accuracy? The following are some analysis of the weak point of IGS legacy products and a direction for the improvement.

- The scientific value of the Final product is in climatology, as there is no direct operational usage for this low latency product. Here the product is hurt by lack of consistency over time. As contributing ACs change their estimation strategy from time to time (e.g., different elevation angle cutoff, mapping function, antenna phase maps), the combined product develops spurious 'climatological' signals. The product availability extends only a few years back, and there is no way to backfill without major coordinated effort from all ACs. Thus, *the IGS Final trop product must be consistent in time, and must be easily regenerated.*

- The Final and UR products may not be sufficiently accurate, as they depend on a rather uneven set of solutions. Indeed, the distribution of the internal quality control metric, the standard deviation among the contributing solution, is quite broad (Figures 1 and 2). Thus, *the IGS Final ad UR tropospheric products should be more consistently of higher quality* (Figure 3).

- The integrity of the Final and UR products is compromised because the only quality control metric is based on inter-comparisons among the contributing solutions, which may have common error sources. Too often there are not enough contributed solutions for a given site, resulting in unrealistically low, or effectively non-existent (zero) sigma. (Figures 1 and 2). Thus, *develop products for which formal errors can be rigorously derived from input. Periodic campaign will validate performance through inter-comparisons with other solutions and techniques.*

- Too few sites in either the Final or the UR products due to relatively small subset of common sites in all AC's contributions. Figure 4 shows the availability of the legacy IGS Final Combined ZPD products in days for each IGS site in year 2003. Since this process depends on the submission of individual solutions from each IGS ACs, the availability of the product is rather limited. This diminishes the scientific and operational benefits from these products. Thus, *the IGS trop product must be available for nearly every site in the IGS network.*

- The UR product is too late for weather forecasting operations. Thus, *the product latency must be at most 3 hours to be useful in operational weather forecasting.*

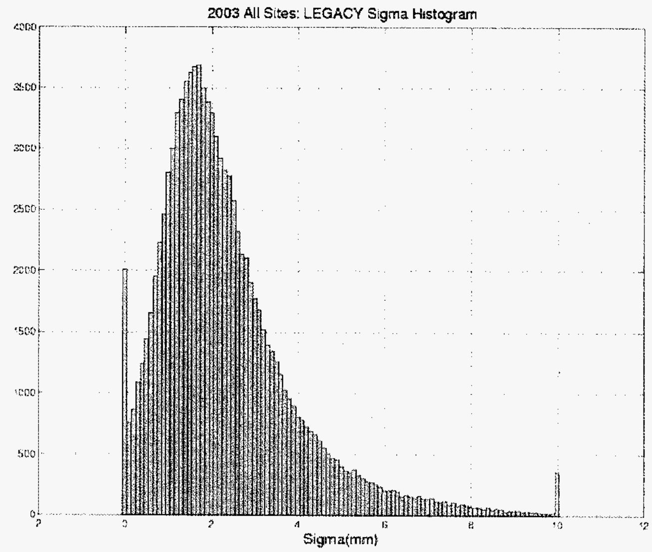

Figure 1. Histrogram of the formal errors reported for the current Combined Final trop solutions. The histogram was generated using all site solutions for 2003. Zero sigma is reported when only one solution is contributed for a given site.

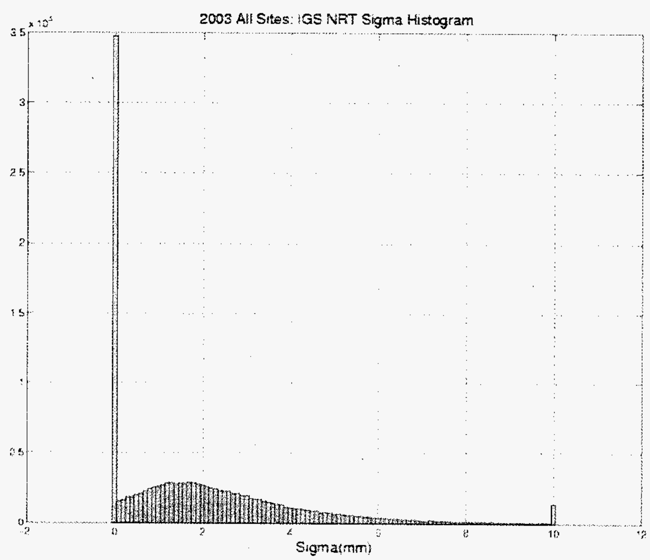

Figure 2. Histrogram of the formal errors reported for the current Combined Ultra Rapid tropospheric solutions. The histogram was generated using all site solutions for 2003. Zero sigma is reported when only one solution is contributed for a given site.

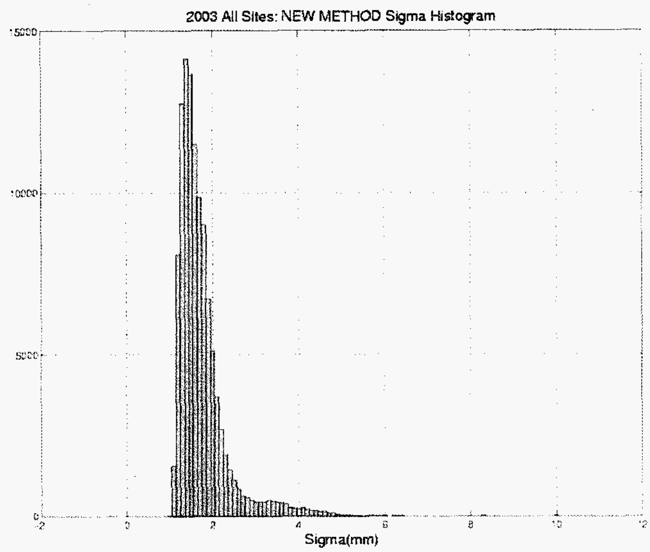

Figure 3. Histrogram of the formal errors reported for the proposed new Final tropospheric solutions (using IGS combined Final GPS orbits and clocks, 7 deg. elevation angle cutoff, estimation zenith delay and gradients as random walk processed, with 5 minute temporal resolution). The histogram was generated from daily point-positioning for a set of ~30 globally-distributed sites during 2003.

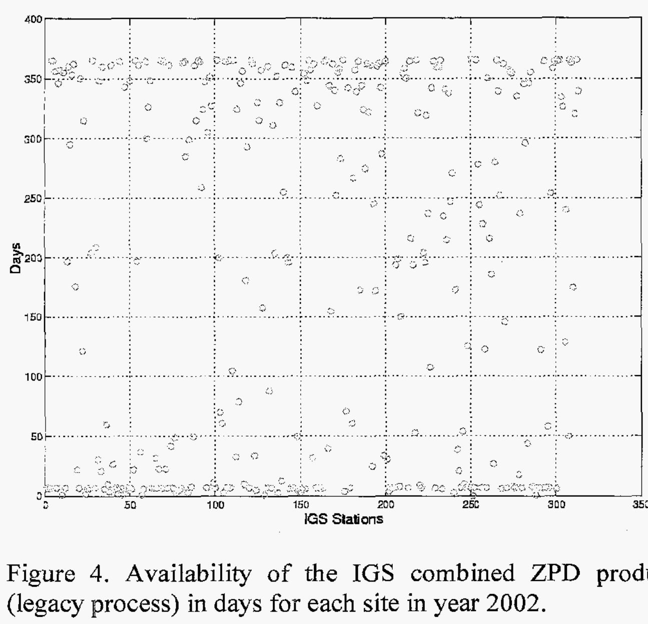

Figure 4. Availability of the IGS combined ZPD product (legacy process) in days for each site in year 2002.

NEW PRODUCTS

In response to these perceived problems in IGS legacy products, a new type of IGS tropospheric product that offers significant quality and operational advantages were proposed in early 2003. The new IGS Tropospheric Product is completely independent of individual contributions by the ACs. Instead these are directly derived from RINEX files from each site with a precise point positioning approach (Zumberge et al.1997) using the IGS Combined Final Orbit/Clock Product. The key to its quality and robustness is the use of the highly accurate and reliable IGS combined GPS orbit and clock solutions. This efficient processing approach allows for the processing of all available IGS sites. The key attributes of the precise point positioning estimation strategy employed to derive the zenith delay estimates for a given site are (Bar-Sever et al. 2003):

- Software: GIPSY
- Fixed orbits and clocks: IGS Final Combined
- Earth orientation: IGS Final Combined
- Transmit antenna phase center: IGS Convention
- Receiver antenna phase center offset: Per IGS data base
- Receiver antenna phase map: None
- Elevation angle cutoff: 7 degrees
- Mapping function (hydrostatic and wet): Niell. (Niell 1996)
- Data arc: 24 hours
- Data rate : 5 minutes
- Estimated parameters: clock (white noise), position (constant), zenith delay (random walk with variance of 3 cm/hour), atmospheric gradients (random walk with variance of 0.3 cm/hour), phase biases (white noise). (Bar-Sever et al. 1998)
- Temporal resolution of zenith delay estimates: 5 minutes

The ZPD estimates derived in this process constitute the new IGS Tropospheric Products. The process produces of a file per site per day. Each file contains a time series of total zenith tropospheric delays with temporal resolution of 5 minutes. The legacy IGS tropospheric file format is used nearly unchanged. Since the files are produced daily instead of weekly, the file name convention was changed from sssswwww.zpd to ssssddd0.yyzpd (ssss is 4 letter IGS station id, wwww is GPS week number, ddd is day of year, and yy is year in two digits). The process to derive the new product has been operational since September 2003. For the time being only the new 'Final' products, derived from the IGS Final Combined GPS orbit and clock solutions are produced. These are currently available at:

ftp://sideshow.jpl.nasa.gov/pub/igs_trop/trop_new
ftp://cddis.gsfc.nasa.gov/pub/gps/products/trop_new

In an effort to create a long and consistent time series of tropospheric delay values, back-processing was carried out spanning back into October 2000 (Note: Official IGS clock solution starts from that month). Similarly deriving a new UR product would require reduced latency for the IGS Combined UR orbit and clock product.

VERIFICATION AND COMPARISON

We have selected thirty well-distributed IGS ground stations to assess the performance of the new strategy for the year 2003. We compared the ZPD values from the new approach to that of the legacy combination method. Figure 5 shows the 30 IGS stations used for this analysis, and figure 6 shows the RMS of ZPD differences in *mm* for each station excluding outliers (3 sigma editing). For "good" stations (predominantly in Europe and North America) the RMS differences are less than 3*mm* level. Figure 7 shows the time series of ZPD difference between the new and legacy approaches for ALGO (Algonquin, Canada), and figure 8 is for EISL (Easter Islands) which turned out to be the site with the largest differences. In any case the outlying points were traced to the solutions with large formal errors in the legacy approach. We believe, therefore, that the technique-based differences between the legacy and the new combination approach are roughly at the 3*mm* RMS level, consistent with the level of formal errors in the state of the art tropospheric retrievals with GPS. Figures 9 and 10 show the formal errors of ZPD solutions from the new and legacy approaches, respectively, for year 2003. As can be seen from the figures, the ZPD values from the new approach possess in general smaller formal errors values than that of legacy combination approach. In figure 10 zero sigma values mean that only one AC submitted the ZPD solution and no meaningful statistics is available.

External quality assessment is essential for any operational product. As a measure of quality assessment both for the new IGS Tropospheric Product and for the tropospheric production at the ACs, the individual submitted ZPD solutions from the AC are compared to the new IGS Tropospheric Product. The resulting comparisons are available as files at:

ftp://sideshow.jpl.nasa.gov/pub/igs_trop/trop_cmp
ftp://cddis.gsfc.nasa.gov/pub/gps/products/trop_cmp

The files containing the comparison information have the naming convention: TROPddd0.yycmp (ddd is day of year, and yy is year in two digits). The same internal file format of the legacy product is used here as well. Unlike the old approach where some submitted tropospheric solutions were edited out and statistics were based on "good" submitted solution, the new approach compares everything without any editing. So the metric values are a bit higher than they used to be, but perhaps more realistic. ZPD comparison files are available from September 26, 2004.

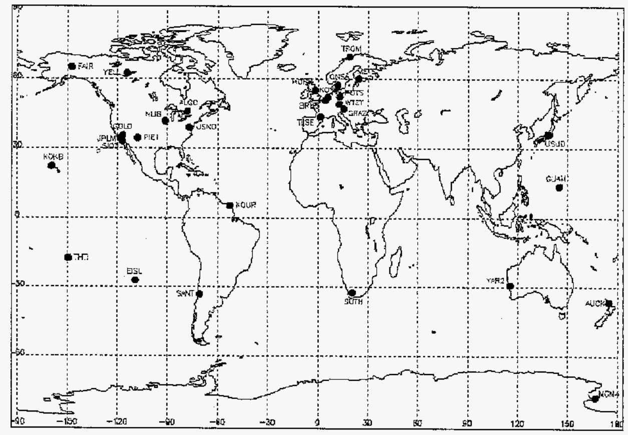

Figure 5. A subset of IGS stations used for the new tropospheric product quality verification.

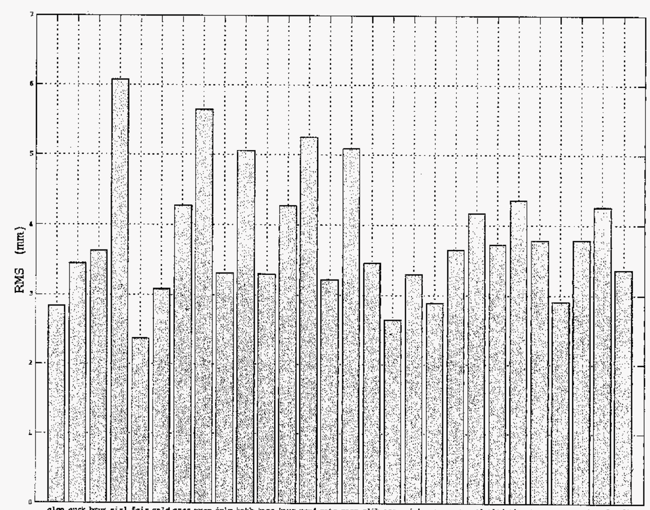

Figure 6. The RMS of ZPD differences between the new and legacy strategies for each site selected for the comparison. X-axis denote the station list in alphabetic order; Y-axis denote the RMS of the ZPD differences in *mm*.

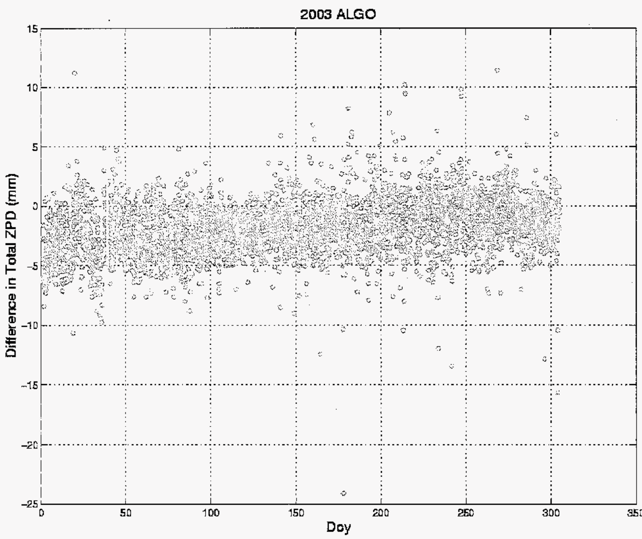

Figure 7. The time series of ZPD differences between the new and legacy approach for ALGO site.

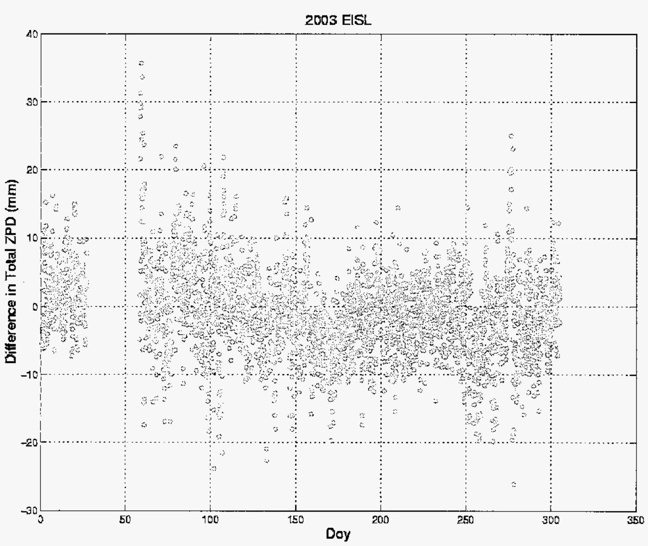

Figure 8. The time series of ZPD differences between the new and legacy approach for EISL site.

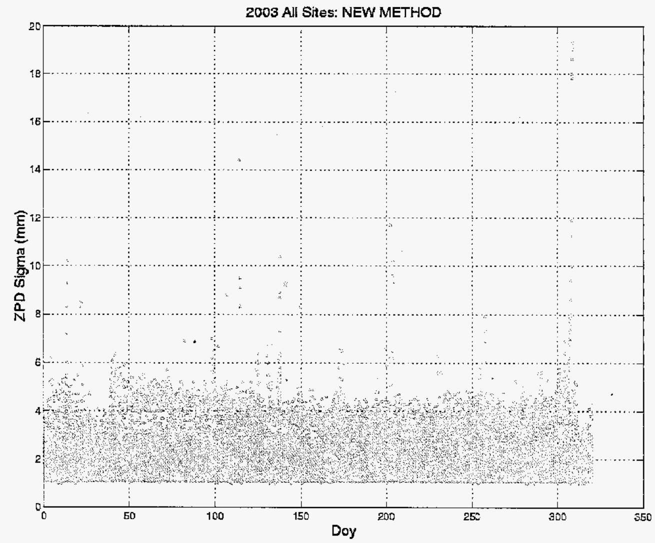

Figure 9. The time series of ZPD sigma of the new approach for all 30 sites.

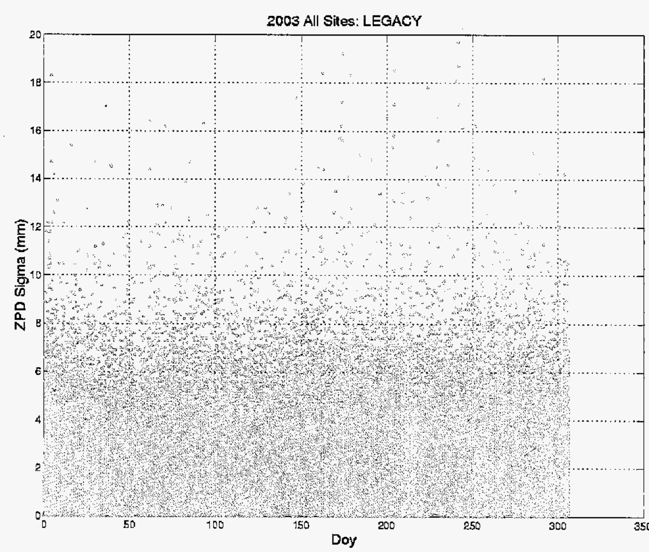

Figure10. The time series of ZPD sigma of the legacy combination approach for all 30 sites.

ADVANTAGES OF THE NEW PRODUCT

There are quite a few noticeable advantages in using the new approach for the IGS tropospheric product generation:

Efficiency:
The new method based on point positioning method is relatively simple compared to optimally combining the submitted ZPD values. The process is more efficient and economical than the legacy process and requires less than 1 min/site/day of CPU time on Linux machine. This enables massive production of ZPD solutions to practically all IGS stations (more than 300 sites per day).

Easy Re-Analysis and Long Term Stability:
The legacy combination process suffers from the inability to perform re-analysis to capitalize on improved estimation strategy, or changes in data. The new approach is not susceptible to changes in estimation strategy at the ACs, and thus is inherently more stable over period of time. This uniform estimation strategy insures long-term stability of the product, which is of critical value to climatology studies. The new process can easily accommodate massive re-analysis, and years of products can be regenerated if better estimation strategy emerges.

Flexibility:
The legacy combination process can produce the combined solution of the site only if the ZPD solutions for that site are provided by several ACs. By using IGS orbit and clock and PPP approach, the new method can produce ZPD for any site with RINEX file. The temporal resolution of the legacy product is two hours. The temporal resolution of the new ZPD product is only constraint by the data rate, and is nominally set at 5 minutes.

Robustness:
The quality of the legacy combined ZPD product for a given site strongly depends on the number of ACs contributing solutions. In contrast, the new approach is based on the robust IGS combined GPS orbit and clock. Thus, the ZPD solution is only dependent on the quality of available RINEX data (Figure 3).

Accuracy:
By using the precise modeling of the troposphere, and low elevation cutoff angle, rather than depending on unreliable individual contribution of the ZPD solution, higher accuracy can be achieved.

Better Quality Control:
Many metrics can be used for the ZPD solution quality control and high integrity of the product under the new approach: postfit residuals, the number of total data points, the number of outliers, site position repeatability, formal errors, the gaps in ZPD solution. Figure 11 shows one of the quality control metrics, the estimated station position deviation from the nominal value. In general the 3D daily repeatability is better than 10*mm* level and any solution with larger difference in station position can be excluded from the official IGS tropospheric solution.

Portability:
The new process is mainly written in highly portable Perl script. Thus, it can be easily ported to other software and platforms environment.

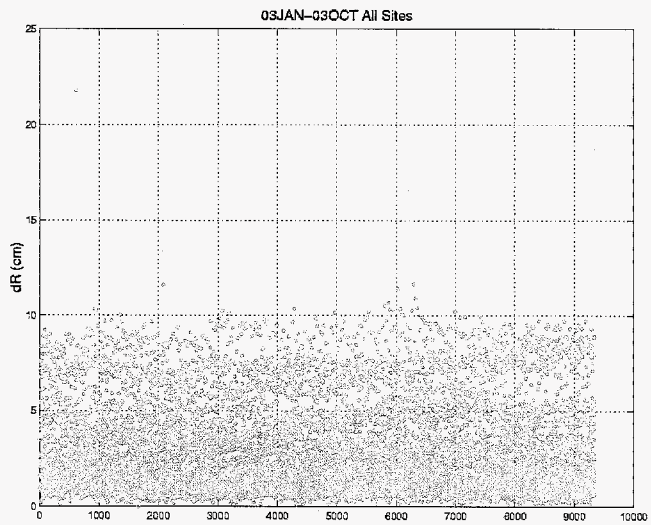

Figure 11. One of new troposheric product quality control metrics: the 3-D station position deviations from the nominal values.

IGS METEOROLOGICAL DATA

The directly estimated ZPD values are of interest for some special applications, such as atmospheric corrections for collocated VLBI or two-color SLR instruments. However, the scientific value of the IGS tropospheric product is in climatology, and to be useful for that application the IGS tropospheric product should be the vertical integrated PWV. For sites equipped with meteorological sensors, the usual daily RINEX-met files can be generated and the ZPD estimates can be converted into integrated PWV (Bevis et al. 1994; Bevis et al. 1992). The number and quantity of the meteorological sensors has been slowly improving. Currently, there are roughly 70 meteorological sensors in the IGS network but the number of instruments available now is not sufficient. Thus, at least at the moment and also for some future period of time there will be a greater number of sites without meteorological sensors, so that only the ZPD information will be available for those sites.

Among the meteorological sensors the accuracy of the atmospheric pressure sensors is most important and critical. For its reduction to the GPS antenna height, the height difference between the pressure sensor and the GPS antenna phase center must be known with an accuracy of 1 *meter* (which corresponds to 0.12 hPa). That means a good documentation on pressure sensor positions is necessary. The simplest way would be to have all information needed directly in the RINEX file.

The atmospheric surface pressure data must be of high precision (1 mbar corresponds to 0.35 mm in PWV) and reliability (continuous time series). Unfortunately, no direct feed-back regarding the accuracy of the pressure sensors can be made from the analysis. The only possible way of checking the sensors is by a regular (e.g. yearly) 'calibration' which is in fact a comparison with a high-precision reference instrument. These precision instruments emerge from the factory calibrated to better than half a mbar, and are typically certified to remain calibrated for three years. Left uncalibrated for more than three years, the meteorological package becomes less than useful, as its data can contaminate PWV measurements derived by combining surface pressure measurement with GPS data. Ensuring good calibration of the various meteorological packages in the IGS network is a logistical and financial challenge for all the responsible agencies. However, it is important thing to do to increase the meteorological and climatological value of the IGS global network. Unfortunately, it is clear the vast majority of meteorological sensors have never been calibrated in the field.

DISCUSSION

The motivation and advantages of the new approach in generating ZPD for IGS official tropospheric product has been discussed. The new approach uses combined IGS orbit and clock information and directly generates the ZPD values for each site using PPP method instead of combining the AC submitted ZPD values. The agreement in RMS between the new approach and the legacy IGS combination approach is better than 4*mm* level. It is demonstrated that the new approach is more precise, robust, and reliable.

The new tropospheric products must be subject to independent periodic quality assessment. It would be desirable to do that through periodic campaigns where collocated WVR and radiosonde measurement are inter-compared with the new IGS tropospheric product. We believe, however, that the new combination process offers sufficient internal quality metrics to ensure high quality and reliability. The simplicity of this new process also enables easy implementation, and allows the generation and inter-comparisons of similarly derived products (but with different software or estimation strategies) of the contributing ACs. As better mathematical models are developed, the new approach can easily implement the emerging new techniques. Examples may include the new GPS transmitter antenna phase center map (Hanes et al. 2004), and the improved mapping functions using the information from numerical weather model (Boehm and Schuh 2004; Niell 2001; Niell 2000)

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